Carbon Management Decision Support Tools Evaluation Report

LobDST Team

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GEOSS Societal Benefit Areas: Climate and Ecosystems

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Decision Support for Forest Carbon Management: From Research to Operations

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Project Objective

The goal of this Integrated System Solutions (Figure 1, below) project is to assimilate NASA Earth science results into a widely used forest management decision support system, LobDSS, so that forest landowners can make informed decisions about thinning and fertilizing with full understanding of the resulting implications for carbon sequestered or emitted (what this project is *adding* to LobDSS) in addition to aboveground product yield (what LobDSS *currently* optimizes).

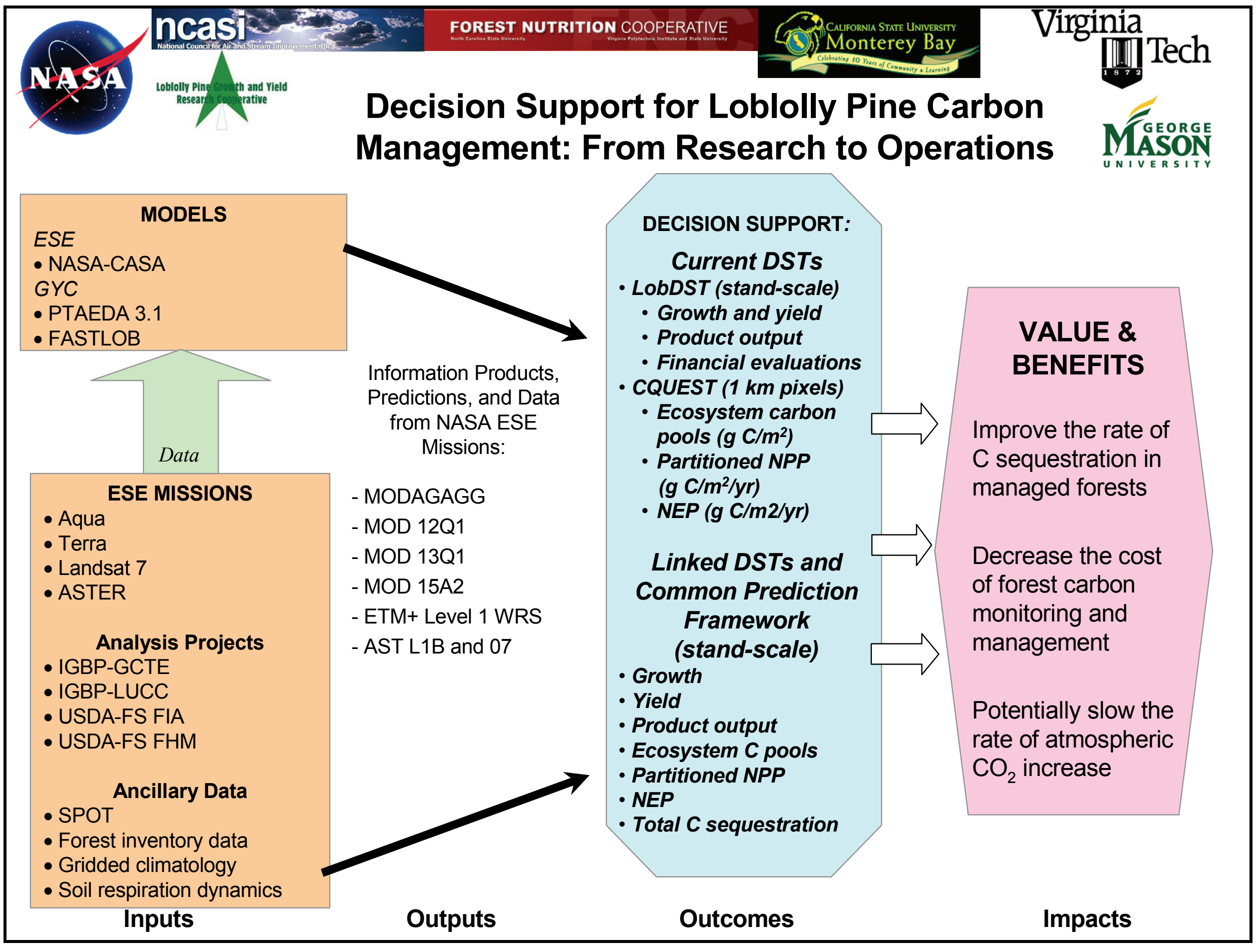

Figure 1 ISS chart.

Introduction

Anthropogenically-induced atmospheric carbon dioxide concentrations continue to increase. A large body of observations and modeling results have shown that this increase, in conjunction with increases in other greenhouse gas concentrations, has been a major driver of observed global warming and other changes in climate (e.g, IPCC 2007). The scientific community has now called for acceleration of research into how ecosystems can help mitigate climate change (National Research Council 2004). Terrestrial ecosystems are impacted by and in turn impact the global carbon cycle and climate (Cao and Woodward 1998). Afforestation and forest growth appears to have already increased global net ecosystem production, NEP, which is net primary production less heterotrophic respiration (Cao and Woodward 1998, Malhi *et al.* 2002). A significant portion of this NEP increase has come from increased productivity of the pine plantations in the Southeast (Siry 2002). Some of this increase in productivity is driven by CO_2 fertilization and climate changes favoring production. Most, however, is due to forest landowners maximizing site productivity through more intensive silvicultural prescriptions (including improved growing stock, site preparation, release from competition, thinning, and fertilization) (Borders and Bailey 2001). Of these, thinning and fertilization are the most widely applied mid-rotation silvicultural treatments and have a large impact on net ecosystem carbon production. Forest landowners have developed decision support tools to help them maximize productivity through wise choice of the type and timing of thinning and fertilization, but these tools do not currently provide information on the resulting changes in ecosystem net carbon balance, including the fate of soil, root, and litter carbon. Reliable information on the carbon costs embodied in silvicultural prescriptions and ecosystem net carbon balance together provide an estimate of carbon sequestration. NASA Earth science results, coupled with results from research sponsored by other agencies, particularly DOE, USDA, NSF, and forest industry, if properly assimilated and extended, will allow the provision of reliable carbon sequestration information to forest landowners. Our stakeholders are keenly interested in gaining access to this information. Many large forest landowners are already participating in functioning carbon markets (e.g., the European Union Emissions Trading Scheme and the Chicago Climate Exchange Carbon Market) and are thus quite interested in how best to manage their forests for increased carbon sequestration. In the aggregate, land management that results in increased carbon sequestration has the potential to reduce the rate of increase of atmospheric carbon dioxide, providing a short-term mitigating effect on climate change.

LobDSS

The Loblolly Pine Decision Support System (LobDSS) encompasses growth and yield prediction equations for the geographic range of loblolly pine and a host of management activities including growing-stock genetic improvement, site preparation, bedding, thinning, mid-rotation fertilization and weed control, and rotation length management. Predictions have been developed and validated at the stand level based on dozens of industrial and research data sets compiled by the Forest Nutrition Cooperative (FNC, jointly administered by NC State and Virginia Tech) and the Loblolly Pine Growth and Yield Research Cooperative (administered by Virginia Tech) (see Table 1 for a partial list of current members in the two coops). The model core (FASTLOB2, see below) is enhanced by productivity modifiers based on soil characteristics and climate conditions. LobDSS provides financial evaluations for a wide range of management activities prescribed throughout the life of a stand. Its interface allows users to predict the growth and yield of a single-stand through a user-friendly GUI, or over a landscape of individual stands when linked to information from a GIS. Because of its core model accuracy and powerful application features, LobDSS and its precursors have gained widespread acceptance among industrial landowners, agencies, and forestry consultants as essential tools for loblolly pine plantation management.

American Forest Management
Augusta Woodlands Corporation
Avinger Timber
Bioforest
Boise
Dougherty & Dougherty Forestry
Forest Investment Associates
Forest Systems
Forestal Mininco
Forestry & Land Inv. Consultants
Gulf States Paper
Hancock Forest Management
International Paper
Jordan Lumber
MeadWestvaco
Milliken Forestry
Molpus Timberlands Management
Mosaic
Plum Creek Timber Company
Potlatch
Rayonier
Regions Morgan Keegan Trust
Resource Management Service
Smurfit Cartón de Columbia
Temple Inland
USDA Forest Service
Weyerhauser

Table 1 FNC and GYC members.

FASTLOB2

FASTLOB2 is a set of stand-level growth and yield models for managed loblolly pine plantations developed using data from permanent remeasurement plots established in 1980-1982 throughout the Piedmont and Coastal Plain areas of the loblolly pine growing region. Stand-level projection equations for dominant height, survival and basal area form the nucleus of a thinned and unthinned baseline model. Functions for intermediate treatments of fertilization were developed from treatment plot data reflecting typical fertilized regimes. The response functions are sensitive to specific fertilization prescriptions (nitrogen and phosphorus) as well as to stand and site conditions at time of treatment. They are used to modify or adjust the baseline models in order to reflect the effects of intermediate fertilizer treatments on stand development after treatment. Level of competing overstory hardwood basal area has been incorporated into the baseline models so the effect of this component of competing vegetation can be simulated if desired.

An expert system consisting of a set of silvicultural responses and rules for implementing them is used by FASTLOB2 to define and grow plantations from establishment. The expert system incorporates the concept of a loblolly pine "base" site index for each of the major soil types in the Southeast and soil specific responses to various treatments including herbaceous weed control, hardwood vegetation control, bedding, combination plowing, and P fertilization at time of planting. The Forest Nutrition Cooperative's soil matrix, base site index values, and treatment response estimations were originally developed by Lee Allen, Bob Campbell, and Jim Gent for the Forest Nutrition Cooperative's Forest Productivity - Silvicultural Relationships workshops in the early 1990s and have been modified and updated as new information has become available during the last 15 years. The soil matrix differentiates major soil groups based on drainage, subsoil texture, and depth of the A horizon and presence or absence of a spodic horizon.

FASTLOB2 can be used for a variety of purposes including evaluating response to thinning, hardwood control and fertilization treatments. Simulation test results show that the growth models in FASTLOB2 provide reasonably precise stand-level predictions when used as an integrated model system. Consequently, the FASTLOB2 model system is suitable for predicting yields of unthinned, thinned and fertilized loblolly pine plantations.

Two software applications have been developed for implementing the FASTLOB2 dynamically linked library of growth and yield models. GYST is a spreadsheet application that allows users to invoke FASTLOB2 in a batch environment. Input data for multiple stands can be specified in GYST and then applied to FASTLOB2 for inventory updating or harvest scheduling purposes on a landscape scale. Output from FASTLOB2 is spooled to GYST where it can be exported to Excel and other applications for further processing.

For evaluating individual simulation runs of FASTLOB2 in a more rigorous environment, the LobDSS application with its graphical and economic analysis tools can be used. LobDSS provides an intuitive interface to receive user inputs for FASTLOB2. Results from FASTLOB2 are directed to the LobDSS output windows and displayed for the entire rotation. Graphical summaries from the simulation are presented in graphics windows and a discounted cash flow analysis is performed based on economic parameters supplied by the user. As with GYST, output can be ported to other software applications via the Windows clipboard for additional analyses.

CASA

The CASA (Carnegie Ames Stanford Approach) model predicts terrestrial ecosystem fluxes using MODIS inputs at a maximum geographic resolution of 250 meters to infer variability in forest carbon fluxes. This model, developed at NASA Ames Research Center, is designed to estimate daily or monthly patterns in carbon fixation, plant biomass increments, nutrient allocation, litter fall, soil carbon/nitrogen and CO_2 exchange, and soil nutrient mineralization. As documented in Potter *et al.*(1999), NPP flux, defined as net fixation of CO_2 by vegetation, is computed in CASA on the basis of light-use efficiency (LUE). Daily or monthly production is estimated as a product of time-varying surface solar irradiance (Sr), and the fraction of absorption of photosynthetically active radiation (fPAR) from the satellite AVHRR, plus a constant LUE term (ε_{max}) that is modified by time-varying stress scalar terms for temperature (T) and moisture (W) effects. NPP of vegetation is predicted using the relationship between leaf reflectance properties and fPAR, assuming that net conversion efficiencies of PAR to plant carbon can be approximated for different ecosystems or are nearly constant across all ecosystems. The ε_{max} term is set uniformly at 0.34 g C MJ-1 PAR for MODIS fPAR, a value that derives from calibration of predicted annual NPP to previous field estimates. This model calibration has been validated globally by comparing predicted annual NPP to more than 1900 field measurements of NPP.

The soil water model design includes three-layer (M1-M3) heat and moisture content computations: surface organic matter, topsoil (0.3 m), and subsoil to rooting depth (1 to 2 m). These layers can differ in soil texture, moisture holding capacity, and carbon-nitrogen dynamics. Water balance in the soil is modeled as the difference between precipitation or volumetric percolation inputs, monthly estimates of PET, and the drainage output for each layer. Inputs from rainfall can recharge the soil layers to field capacity. Excess water percolates through to lower layers and may eventually leave the system as seepage and runoff. Freeze-thaw dynamics with soil depth operate according to the empirical degree-day accumulation method (Potter *et al.* 1999).

The CASA model designed at NASA Ames Research Center has coupled daily and seasonal patterns in soil nutrient mineralization and soil heterotrophic respiration (R_h) of CO_2

from soils. NEP is computed as NPP minus R_h fluxes. CASA's soil carbon model uses a set of compartmentalized difference equations with a structure comparable to the CENTURY ecosystem model (Parton *et al.*, 1993). First-order decay equations simulate exchanges of decomposing plant residue (metabolic and structural fractions) at the soil surface. The model also simulates surface soil organic matter (SOM) fractions that presumably vary in age and chemical composition. Turnover of active (microbial biomass and labile substrates), slow (chemically protected), and passive (physically protected) fractions of the SOM are represented. Along with moisture availability and litter quality, the predicted soil temperature in the M1 layer controls SOM decomposition.

Extension of Earth Science Results

The empirical models in LobDSS are among the best tools currently available for predicting stand-level growth and yield over a defined range of environmental conditions and management practices. CASA is designed to make regional predictions of carbon and nutrient cycling driven by remote sensing data, ecophysiological parameters, and climate inputs.

Through a series of computer simulations and computational analyses, we are jointly calibrating and linking LobDSS and CASA/CQUEST through a framework that incorporates a wide range of knowledge from past research of the investigative team and published results from other studies. Available data sets not already incorporated into either model's development are being used to minimize model prediction uncertainties and make model improvements where warranted. The resulting common prediction framework is being designed to make joint predictions of growth, yield, product output, and carbon pool dynamics at exchangeable scales.

Methods

CASA Model Refinements

Tasks for refinements and testing of the existing CASA model are outlined below for new carbon cycle simulations of forest management (thinning harvest and nitrogen fertilization), followed by long-term projected regrowth effects on overall carbon balance (NEP) at the stand scale. (1) Changes in monthly fPAR values as inputs to CASA will be made to match observed changes in forest canopy cover on nitrogen fertilization study plots. (2) Changes in the potential rate of soil microbial carbon and nitrogen turnover in CASA will be made to match observed changes in soil processes on nitrogen fertilization and thinning study plots. (3) Evaluation of changes in the size of soil organic matter carbon pools in CASA will be made in comparative analyses of observed changes in soil carbon pools on nitrogen fertilization and thinning study plots. (4) Uncertainties in CASA model predictions of soil CO_2 emissions will be assessed in comparative analyses of observed changes in soil CO_2 emissions on nitrogen fertilization study plots.

Adding Carbon to FASTLOB2

As outlined in our original proposal, we have now completed the upgrade to FASTLOB (now version 2.1) and LobDSS. The major additions and changes include biomass equations for estimating stem (with bark), branch (with bark), foliage (first and second year cohorts), coarse roots (including tap root), fine roots and coarse woody debris of the loblolly pine component of the plantation. The biomass equations were gleaned from the literature, but the coarse woody debris equation is from new research (unpublished but in the works). All this is documented in the updated version of the FASTLOB manual (FASTLOB21.pdf, available upon request). These new equations are now being rigorously tested.

Product Lifecycle and Carbon Costs of Fertilization

LobDSS enables users to evaluate impacts of silvicultural treatments on resulting forest stand characteristics. Because the selection of silvicultural treatment also involves economic and management parameters (such as rotation length, treatment costs, and product values), LobDST goes well beyond biological modeling. The evaluation of carbon impacts therefore must incorporate some of these same considerations. For example, selection of rotation length has an impact on longevity of carbon storage in the forest as well as an impact on the product distribution (pulpwood/sawtimber) and product value. Furthermore, because forest products have substantially different carbon retention rates, silvicultural decisions have carbon impacts that outlive the forest stands themselves. The international forest products industry has settled on an approach, called the 100-year method, for entity-level estimations of the carbon sequestration benefits associated with forest products in use (Miner 2003). The concept can also be extended to address carbon storage in products disposed in landfills. NCASI, the organization that has worked with the industry internationally to gain recognition of the 100-year method, is integrating this approach into the tools developed in this study so that these long-term storage benefits are recognized.

Increased forest productivity resulting from fertilization may increase carbon sequestration in forest biomass. However, the carbon emitted from fossil fuel use associated with the manufacturing, packaging, transport, and application of fertilizer is often ignored. NCASI has done a preliminary analysis of the carbon costs of fertilization using a modification of an approach developed for agricultural systems (Bhat et al. 1994). This analysis will be applied to typical fertilizer applications in southeastern pine plantations to estimate carbon costs and net sequestration (benefits - costs) under different levels of forest productivity response.

Soil Respiration Verification and Validation

Accurate estimates of soil respiration are critical for reliable estimates of NEP. Soil CO_2 efflux represents a significant portion of total ecosystem respiration (Janssens et al. 2000), often comprising 50 to 80% of the total (Lavigne et al. 1997). A central weakness in broad-scale assessments of net carbon balance is our relative inability, to date, to accurately model soil respiration. This is particularly true when modeling soil respiration as impacted by stand management. The southern pine ecosystem represents 29% of the total forest land in the United States (Conner and Hartsell 2003) and is some of the most intensively managed forest land in the world. As in most ecosystems soil respiration represents a large portion of loblolly pine ecosystem respiration.Verification and validation of CASA estimates of NEP will require a clear understanding of how soil CO_2 efflux varies across the range of conditions in managed loblolly pine.

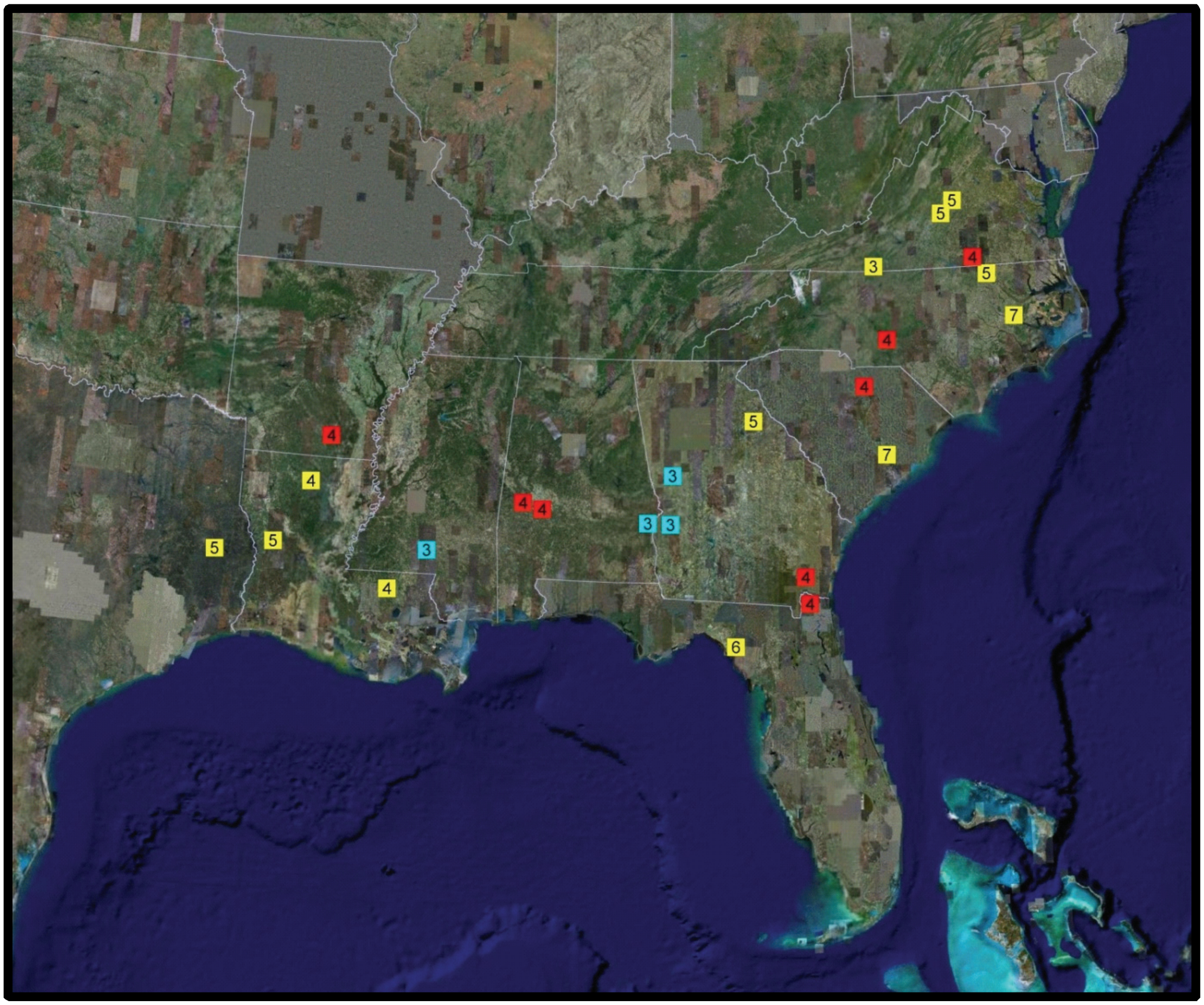

Figure 2 Soil sampling locations.

To develop an accurate soil CO_2 efflux model enabling verification and validation of CASA NEP estimates, a series of survey sites throughout the managed range of loblolly pine is being sampled (Figure 2, above). We are making use of FNC and GYC study sites located across the Southeast. Study sites were selected from existing plantations subjected to fertilization and thinning, two dominant management practices used throughout managed loblolly pine ecosystem. On each site standard mensurational data are collected using fixed plots. Plot size and type vary among sites depending on the extent of ancillary data available at the shared plot locations. Mensurational data include stand age, tree species, height, stem diameter (dbh), height to live crown, and stem x,y coordinates for mapping. Soils at each site are also described taxonomically. Total soil CO_2 efflux is being measured using the Li-Cor 6200 infrared gas analyzer (IRGA) (Li-Cor Inc., Lincoln, Nebraska) and a dynamic closed cuvette chamber system (Janssens et al. 2000). Measurements are being taken 3 times throughout the year to obtain a wide range of temperatures and soil moistures (determined each time soil respiration is measured). Soil texture, soil pH, CEC, base saturation, extractable nutrients (P, K, Ca, Mg, S, etc) and total N are also being determined (Klute 1986).

Remote Sensing at the Scale of Management

For decision support for forest landowners data sets derived for use at the regional to continental scale must be supplemented by remote sensing at the scale of forest management. In our particular case, the 250 m vegetation index products used by CASA will have to be spatially downscaled – while maintaining current temporal resolution – because of parcel size. In Virginia, for example, the average parcel size for forest land is now 30 hectares (under five 250 m MODIS pixels) and decreasing. The data from sensors aboard Landsat (which has non-functional scan-line detector artifacts in scenes acquired from June, 2003 to present) and relatively similar (e.g., SPOT, ASTER, etc.) medium-resolution earth resource satellites have the appropriate spatial and spectral resolutions with which to downscale.

We are implementing an empirically-based downscaling solution based on a unique nature of this ISS: most of the forest landowners we are serving already know a great deal about their holdings. Typical information contained in forest resource information systems, organized by stand, includes species, establishment date, initial planting density, a recent volume measurement, date and type of each silvicultural prescription, and a modeled estimate of current volume – thereby establishing the site conditions. We know that LAI of loblolly pine varies almost twofold annually, with a double foliage cohort at peak LAI (September) and a single cohort just prior to the onset of spring growth (March-April) (Kinerson et al. 1974, Sampson et al. 2003). At a minimum, therefore, we obtain four clear Landsat or SPOT images as close as possible to maximum LAI and minimum LAI in each year of a given two year period. After coregistration to the MODIS data sets and conversion to reflectance, NDVI is computed on each image. (We had hoped to use EVI, but observed biases between MODIS and Landsat EVI precluded this possibility.) Fortunately, maximum LAI rarely exceeds four in the range of application, so NDVI saturation with high leaf area is much less of a problem than it can be in other forest ecosystems. The MODIS reprojection tool is used to project the v. 5 (when available) or v. 4 (when not) 250-m NDVI product to UTM WGS-84, the projection of our terrain-corrected Landsat scenes. The pure pine pixels in the MODIS scenes are then identified using an unsupervised classification of the NDVI bi-annual temporal signature, then used to assign a phenological trajectory to the Landsat pine pixels that are most proximate both spectrally and spatially.

Systems Engineering Approach

The principles of the systems engineering process will be used to evaluate the specific DSS design for this project. This involves addressing the key phases within the systems engineering process, i.e. conceptual and preliminary design, detailed design, production, utilization/support, phase out, and disposal. The conceptual and preliminary design phases map to the identification of requirements and specifications of the DSS whereas detailed design, production, utilization/support, phase out and disposal map to the design and implementation of integrated system solutions. The verification and validation as well as the benchmarking phases are consistent with the testing and design reviews that are part of any life-cycle system design.

One of the mechanisms for achieving this system engineering process evaluation will be to assign a specific group of students that are part of the Virginia Tech ENGR 5204: *Systems Engineering Project* course to this effort. This group will be supervised throughout the duration of the project by the course instructor and data and information will be obtained from key stakeholders that are part of the loblolly pine carbon management project. The objectives of this project will be to demonstrate that the key systems engineering phases have been executed and at the same time propose meaningful improvements both to the implementation of the systems engineering process for earth science applications as well as the actual DSS design. As part of the verification and validation phase critical dynamics will be explored. Our verification and validation report will be completed in conjunction with a demonstration of the LobDSS carbon management prototype to a subset of co-op member companies managing carbon resources in woody biomass and/or soils. As part of the benchmarking effort the use of analytical approaches that can determine best practices, peers and performance targets will be used to quantify the benefit of the project to the member companies of the two research cooperatives.

Issues and Solutions

Several items have been identified in our work to date that have slightly delayed us. One, as noted, we were forced to switch to NDVI from EVI because of observed biases between the Landsat- and MODIS-derived EVI values in pines. Second, our initial study area in Virginia (Landsat scene 16/34) has less information on historical forest management than originally anticipated, due in part to the reduction in industrial forest ownership in the area. This is being addressed by (1) ensuring that the next two study areas contain extensive holdings by cooperating forest products companies in North Carolina and Alabama and (2) assigning approximate stand ages using Landsat chronosequences in all study areas. All other project foci are within their originally scoped timeline. Based on our work to date this project is inherently feasible, and we see no insurmountable barriers to the planned verification and validation using a working prototype in late winter or early spring of 2008.

Literature Cited

Borders, B.E., and R.L. Bailey, 2001. Loblolly pine - pushing the limits of growth. *Southern Journal of Applied Forestry* **25**(2):1-6.

Cao, M., and F.I. Woodward, 1998. Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. *Nature* **393**(6682): 249-252.

Conner, R.C., and A.J. Hartsell, 2002. Forest area and conditions. pp. 357-401 IN: Wear, D.N. and Greis, J.G. (eds.). Southern Forest Resource Assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: USDA Forest Service, Southern Research Station. 635 pp.

IPCC (Intergovernmental Panel on Climate Change), 2007. Working Group I Technical Summary.

Janssens, I.A., A.S. Kowalski, B. Longdoz, and R. Ceulemans, 2000. Assessing forest soil CO_2 efflux: an *in situ* comparison of four techniques. *Tree Physiology* **20**:23-32.

Kinerson, R.S., K.O. Higginbottom, and R.F. Chapman, 1974. The dynamics of foliage distribution within a forest canopy. *Journal of Applied Ecology* **11**:347-353.

Klute, A. (editor), 1986. *Methods of Soil Analysis, Part 1. Physical and Mineralogical Properties*, (2nd edition). Soil Science Society of America, Madison, WI.

Lavigne, M.B., M.G. Ryan, *et al.*, 1997. Comparing nocturnal eddy covariance measurements to estimates of ecosystem respiration made by scaling chamber measurements at six coniferous boreal sites. *Journal of Geophysical Research* **102**:28977-28985.

Malhi, Y., P. Meir and S. Brown, 2002. Forests, carbon and global climate. *Philosophical Transactions of the Royal Society of London A* **360**(1797): 1567-1591.

Miner, R., 2003. Characterizing carbon sequestration in forest products along the value chain. Climate Change Working Group of the International Council of Forest and Paper Associations.

National Research Council, 2004. *Implementing Climate and Global Change Research: A Review of the Final U.S. Climate Change Science Program Strategic Plan*. Washington, DC, National Academies Press.

Parton W.J., et al., 1993. Observations and modeling of biomass and soil organic-matter dynamics for the grassland biome worldwide. *Global Biogeochemical Cycles* **7**(4):785-809.

Potter, C.S., S.A. Klooster and V.B. Brooks, 1999. Interannual variability in terrestrial net primary production: Exploration of trends and controls on regional to global scales. *Ecosystems* **2**(1): 36-48.

Sampson, D.A., T.J. Albaugh, K.H. Johnsen, H.L. Allen, and S.J. Zarnoch, 2003. Monthly leaf area index estimates from point-in-time measurements and needle physiology for *Pinus taeda*. *Canadian Journal of Forest Research* **33**:2477-2490.

Siry, J.P., 2002. Intensive timber management practices. Southern Forest Resource Assessment (D.N. Wear and J.G. Greis, editors). General Technical Report SRS-53, USDA Forest Service Southern Research Station, 635 p.